K^+ production in relativistic heavy-ion collisions

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Recent experimental data on K^+ production at 2.1 GeV/nucleon are not explained by either the cascade model or the fireball model. Here we introduce a hybrid model in which the total kaon yield is given by individual nucleon-nucleon collisions but its momentum distribution is determined by the temperature of the pion. The model is able to explain the data. The possibility of studying K^+ yield as a signature for the pionic instability in heavy-ion collisions is indicated.

[NUCLEAR REACTIONS K^+ production, $K^+-\pi$ interaction.]

Recently, experiments[1] were carried out in Berkeley to measure the K^+ spectrum in relativistic heavy-ion collisions. The motivation of these experiments was the hope of learning about the initial stage of the collision process. The reason that K^+ serves as such an appropriate observable is that it interacts weakly with nucleons (with a total cross section $\approx$10 mb) and therefore has a relatively long mean free path in nuclear matter ($\approx$7 fm). This implies that once a K^+ is produced, it most likely leaves the nuclear matter without interacting with the nucleons. This contrasts with the nucleons and pions which interact strongly with nucleons and, hence, carry information about the final stages of the collision process. Preliminary data on the K^+ spectrum are already available.

A theoretical study of K^+ production in relativistic nuclear collisions using the linear cascade model has been reported by Randrup and Ko.[2] In their study, the production of K^+ is treated perturbatively, that is, the effect of K^+ production on the propagation of nucleons is neglected. Due to the small ratio ($\approx$0.1%) of the K^+ production cross section to the nucleon-nucleon total cross section, this perturbative approach might be appropriate. The input to the calculation is the K^+ angular and energy distributions from baryon-baryon collisions. From the limited experimental data on K^+ production in p-p collisions, a simple one-pion exchange model has been used to parametrize the K^+ distributions. The theoretical predictions of Randrup and Ko, however, underestimate appreciably the K^+ momentum distribution at large angles when compared with the preliminary data of Schnetzer *et al.*[1] On the other hand, Asai, Sato, and Sano[3] have carried out the nuclear fireball model calculations for kaon production. They assume that N, π, Δ, Λ, Σ, and K are in chemical equilibrium. Using a freeze-out density $\rho=0.14$ fm^{-3}, they found that the experimental proton and pion spectra can be reproduced reasonably well. As for K^+, only the slopes of the experimental spectra are well explained by the model; the absolute yield is a factor of 40 larger than the data. This observation agrees with the unpublished results of the author.

Various suggestions have been proposed for understanding the experimental data. Schnetzer *et al.*[4] suggest that high energy pions (with energy above $\approx$700 MeV) produced in the collision may collide with nucleons to produce K^+ with large momentum and at large angles. It is not known yet how important this effect is. Randrup[5] has extended the cascade calculations of Ref. 2 by allowing the K^+ produced in baryon-baryon collisions to interact with the nucleon before leaving the nuclear matter. His preliminary calculation shows that it is possible to make the calculation of Ref. 2 agree with the data in Ref. 1 if proper adjustment is made on the number of rescatterings by nucleons.

Based on the fact that the number of pions produced in these reactions is comparable to or even larger than the participating number of nucleons and that the K^+ interacts strongly with pions because of the p-wave resonance K^* (891 MeV), one expects that it is more likely that the K^+, on its way out of the collision region, would be rescattered by pions rather than nucleons. To put it more quantitatively, let us estimate the total cross section of K^+ with pion. We assume that a single resonance with angular momentum J dominates the reaction. In this case, we have

$$\sigma_{K^+\pi}=4\pi(2J+1)/k^2\,, \tag{1}$$

where k is the momentum of K^+ or π in the center-of-mass system at the resonance energy. For the K^* resonance, we have $J=1$ and $k\approx1.45$ fm^{-1}. Then the total cross section in Eq. (1) is $\approx$180 mb. If we further assume that only the isospin $\frac{1}{2}$ channel contributes to the cross section because K^*

has $I=\frac{1}{2}$, the following relation holds for the total cross section:

$$\sigma_{K^+\pi^+}:\sigma_{K^+\pi^0}:\sigma_{K^+\pi^-}=0:1:2\,. \tag{2}$$

Consequently, the average $K^+\pi$ total cross section is

$$\sigma_{K^+\pi}=\tfrac{1}{3}\left(0+\tfrac{1}{3}\times 180+\tfrac{2}{3}\times 180\right)=60\text{ mb}\,. \tag{3}$$

The first factor $\frac{1}{3}$ occurs because we assume that the pion has equal probability in its three charge states. The $K^+\pi$ cross section is therefore a factor of 6 larger than the K^+N cross section. Including the finite width ($\Gamma \approx 50$ MeV) of K^* would effectively reduce the cross section; but the inclusion of the isospin $\frac{3}{2}$ channel and other partial waves would increase the cross section again. Hence, we expect that, on the average, $\sigma_{K^+\pi} \gg \sigma_{K^+N}$.

In order to include the effect that K^+ is predominantly rescattered by pions, we propose a simple hybrid model for K^+ production in relativistic heavy-ion collisions. In this model, we assume that kaons are produced by nucleon-nucleon collisions as in the model of Randrup and Ko. Since we are interested in energy regions which are only slightly above the K^+ production threshold (1.5 GeV/nucleon), kaons are produced mainly from the first encounter between a projectile nucleon and a target nucleon. For 2.1 GeV/nucleon, the calculation of Randrup and Ko shows that more than half the kaon yield is from these nucleon-nucleon collisions.

The momentum distribution of the kaons, however, is assumed to be determined by the condition that they are in kinetic equilibrium with pions. The kaon temperature is therefore governed by the temperature of the pion. To determine this temperature, we assume that pions are in chemical equilibrium with nucleons and deltas. Together they form the conventional fireball.

For collisions with equal mass projectile and target, the kaon inclusive cross section in the laboratory can then be expressed quantitatively as

$$\epsilon\,\frac{d^2\sigma}{p^2 dp\, d\Omega} \simeq \gamma(\epsilon-\beta p\cos\theta)\,e^{-[\gamma(\epsilon-\beta p\cos\theta)-M_K]/T} \times (2\pi M_K T)^{-3/2}\sigma_K\,. \tag{4}$$

Here p and ϵ are the momentum and energy of K^+, respectively, β is the velocity of the fireball, and $\gamma=(1-\beta^2)^{-1/2}$. The temperature of the fireball is denoted by T, while the mass of K^+ is $M_K=494$ MeV. The cross section σ_K is the total inclusive K^+ cross section as calculated by Randrup and Ko. It is roughly given by $AB\langle\sigma_{NN}^K\rangle$, with A and B the projectile and target masses, respectively. The average K^+ production cross section $\langle\sigma_{NN}^K\rangle$ is approximately one-thousandth of the nucleon-nucleon total cross section, i.e., $\langle\sigma_{NN}^K\rangle \approx 30$ μb at 2.1 GeV/nucleon.

For the case of Ne on NaF at 2.1 GeV/nucleon, the velocity of the fireball is $\beta=0.7\,c$. The temperature of the fireball according to Ref. 3 is 115 MeV if only pions, nucleons, and deltas are in chemical equilibrium. The cross section σ_K is taken to be 9 mb from Ref. 2 and is slightly smaller than the above estimate. We then obtain the K^+ inclusive cross section, as shown by solid curves in Fig. 1, and observe that the calculated K^+ spectra agree with the data in both magnitude and slope.

To further test the model introduced in this paper, we have to pursue the following two studies. First, we must generalize the model to collisions between asymmetric systems and compare it with the data. Unfortunately, such data are still preliminary. Furthermore, the simple formula introduced above in Eq. (4) has to be modified. Second, we should compare our model to the realistic cascade model, taking into account the interaction of K^+ with both nucleons and pions. In order to do this, a more accurate estimate of the $K^+\pi$ cross section based on reasonable theoretical models is needed.

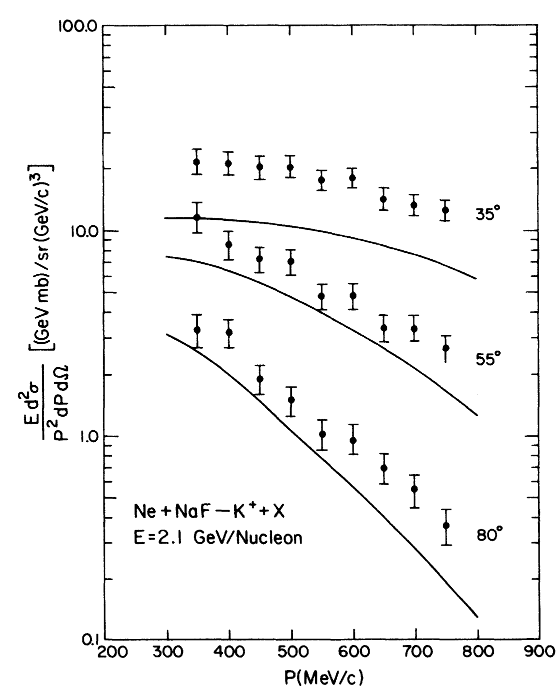

FIG. 1. K^+ momentum distribution in the laboratory from the reaction Ne on NaF at 2.1 GeV/nucleon. The experimental data are from Ref. 1. The solid curves are from the model calculation described in the paper.

The model proposed in this paper can also be tested using coincident experiments. Since K^+ interacts strongly with π^- but very weakly with π^+, we expect strong correlation between K^+ and π^- rather than between K^+ and π^+. If one can measure the coincidence of K^+ with pions around the resonance energy, one should be able to test the validity of the model.

The study of K^+ production in heavy-ion collisions is of importance in another respect. We know that K^+ production from nucleon-nucleon collisions is describable in terms of the one-pion exchange model. In the initial stage of heavy-ion reactions, it is very probable that nuclear matter of a density more than twice the normal density exists. If there is any pionic instability present at such high density, we should expect that some kinematic regions would show an enhanced K^+ yield, more than that predicted in Ref. 2. Since K^+ is unlikely to be reabsorbed due to the conservation of strangeness, we would still expect some enhancement of the total K^+ yields even if they are rescattered by other hadrons. This is very different from pion production. Although the pion production rate in the presence of such a pionic instability is similarly enhanced, its absorption rate by nucleons is equally increased. Therefore, pions produce no net effect. Certainly, a more careful analysis of the K^+ production, taking into account the above-mentioned effect, is required before one can hope to detect it experimentally.

Note added in proof. The data in Fig. 1 are the new data from Berkeley. We have not attempted to modify the calculations which agree better with the original data.

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